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The impact of socio-economic development and climate change on *E. coli* loads and concentrations in Kabul River, Pakistan

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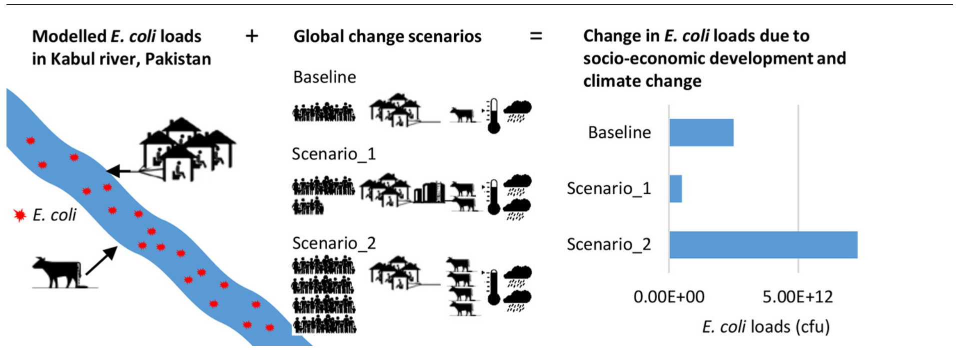
HIGHLIGHTS

- *E. coli* concentrations are influenced by socio-economic development and climate change.
- The SWAT model is run for Kabul river with scenarios based on IPPC's SSPs and RCPs.
- *E. coli* concentrations are large and expected to double in a BAU scenario.
- Concentrations are expected to reduce to 0.6–7% of baseline in a sustainable scenario.
- Reduction of *E. coli* concentrations in Kabul river requires stringent measures.

GRAPHICAL ABSTRACT



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ABSTRACT

Microbial pollution is a major problem worldwide. High concentrations of *Escherichia coli* have been found in Kabul River in Pakistan. *E. coli* concentrations vary under different socio-economic conditions, such as population and livestock densities, urbanisation, sanitation and treatment of wastewater and manure, and climate-change aspects, such as floods and droughts. In this paper, we assess potential future *E. coli* loads and concentrations in the Kabul River using the Soil and Water Assessment Tool with scenarios that are based on the most recent Shared Socio-economic Pathways and Representative Concentration Pathways (SSPs and RCPs) developed for the Intergovernmental Panel on Climate Change (IPCC). Scenario_1 considers moderate population and livestock density growth, planned urbanisation and strongly improved wastewater and manure treatment (based on SSP1, "Sustainability"), and moderate climate change (RCP4.5, moderate greenhouse gas (GHG) emissions). Scenario_2 considers strong population and livestock density growth, moderate urbanisation, slightly improved wastewater treatment, no manure treatment (based on SSP3, "Regional rivalry") and strong climate change (RCP8.5, high GHG emissions). Simulated *E. coli* responses to Scenario_2 suggest a mid-century increase in loads by 111% and a late century increase of 201% compared to baseline loads. Similarly, simulated *E. coli* loads are reduced by 60% for the mid-century and 78% for the late century compared to the baseline loads. When additional treatment is simulated in Scenario_1, the loads are reduced even further by 94%, 92% and 99.3% compared to the baseline concentrations when additional tertiary treatment, manure treatment or both have been applied respectively. This study is one of the first to apply combined socio-economic development and climate change scenario analysis with an *E. coli* concentration model to better understand how these concentrations may change in the future. The scenario analysis shows that reducing *E. coli* concentrations in

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Pakistan's rivers is possible, but requires strongly improved waste water treatment and manure management measures.

1. Introduction

Safe and clean water is essential for human health. However, due to the increasing pressure of population growth, urbanisation and lack of sanitation, safe and clean water is difficult to sustain. Water contamination due to microbiological contaminants (e.g. bacteria, viruses or parasites) impairs the water quality in these systems. Waterborne pathogens may cause diseases, such as diarrhoea, which is the fourth leading cause of death in children under five years of age (UN, 2015). To analyse the microbial contamination in water systems, often faecal indicator bacteria are used, such as faecal coliforms and *Escherichia coli* (*E. coli*) (Coffey et al., 2007; Odonkor and Ampofo, 2013). Although *E. coli* is most often not pathogenic, its presence in high concentrations may indicate faecal contamination, and the possible presence of pathogenic microorganisms, and therefore an increased human health risk (Wu et al., 2011).

Concentrations of *E. coli* in surface water systems fluctuate with changing socio-economic variables, such as population growth, urbanisation and sanitation, and climate change, which includes variations in surface air temperature and precipitation patterns. Examples of the mechanisms that influence *E. coli* concentrations in surface water are ubiquitous. While, for instance, a properly constructed pit latrine leaches minimal microorganisms to the water system, a sewer without treatment emits large amounts (Graham and Polizzotto, 2013). Increases in population put pressure on sanitation systems. Moreover, climate-change induced extreme precipitation may increase microbiological discharges to surface water through an increased number of sewer overflows and manure runoff from the land. Conversely, increased precipitation may also increase dilution and therefore reduce surface water concentrations (Boxall et al., 2009; Rose et al., 2001; Whitehead et al., 2009). The potential overall impact of socio-economic development and climate change on microbial contamination of surface water is understudied (Hofstra and Vermeulen, 2016).

To assess the impact of socio-economic development and climate change on *E. coli* concentrations in surface water systems, researchers may apply scenario analysis using mathematical models (Hofstra, 2011). Scenario analysis explores future developments in complex systems. Scenario analysis is standard practice in other climate impact fields. Relevant examples of such scenario analyses include Ridley et al. (2013) and Wiltshire (2014), who explained the projected increases in precipitation in the Hindukush Karakorum Himalayan (HKH) region, including the Kabul River Basin, in the mid to end of the 21st century. Vörösmarty et al. (2010), highlighted the importance of freshwater stress in the face of climate change and found that approximately 80% of the world's population is at risk of water security. Climate change impacts on microbial water quality have been discussed by Jalliffier-Verne et al. (2017), who applied a hydrodynamic model to simulate the transport of faecal contaminants from combined sewer overflows affecting drinking water quality in Quebec, Canada. They found an increase in *E. coli* concentrations of up to 87%, depending on future climate and population changes in the worst case scenario. Rankinen et al. (2016) used the INCA-Pathogen model in the agricultural Lominijoki River Basin in Finland and concluded that pathogen concentrations in surface water are expected to be diluted due to increased precipitation in the future and that the water quality will not be deteriorated due to future agricultural expansion when the animal density remains relatively low and manure used as fertilizer is pretreated. They also concluded that the water quality in the basin can be improved substantially if wastewater treatment would be improved. Similarly, Sterk et al. (2016) found that overall climate change has limited impact on runoff of waterborne pathogens from land to surface water. In most of these analyses, climate change scenarios were utilized. Islam et al. (2018) is, to the authors' knowledge, the only study that assessed the impacts of combined socio-economic development and climate change on microbial water quality. They found that for a case study in Bangladesh socio-economic development influenced the microbial water quality more than climate change and that for a sustainable scenario loads could be strongly reduced.

The objective of our study is to assess the effects of potential future socio-economic development and climate change on *E. coli* loads and concentrations. As an example, we apply this generic assessment to Kabul River in Pakistan. High concentrations of *E. coli* are found in the main stream and tributaries of Kabul River. Bathing water criteria are violated year round and floods strongly increase concentrations due to increased runoff of manure from the land (Iqbal et al., 2017). This suggests that people who use the contaminated water for bathing, cleaning and other domestic activities are at risk of waterborne diseases. We developed scenarios (Section 2.3) based on the state-of-the-art scenarios used for the most recent Intergovernmental Panel on Climate Change (IPCC) assessment and created specific assumptions for the Kabul River Basin that are in line with the storylines. We apply these scenarios within a Soil and Water Assessment Tool (SWAT, Moriasi et al., 2015) based-model (Section 2.2) that has been calibrated and validated for hydrology and monthly *E. coli* concentrations in earlier publications (Iqbal et al., 2018; Iqbal and Hofstra, 2018). This scenario-based approach helps researchers and water managers to understand what possible futures could emerge and to identify alternative pathways to improve the Kabul River's impaired water quality contaminated with microbial pollutants. The approach could also be applied to other river basins in the world.

2. Data and methods

2.1. Study area

Our study was conducted in the Kabul River Basin (Fig. 1). The characteristics of this watershed have been described in detail by Iqbal et al. (2018). The River basin covers 92.6×10^3 km^2 and frequently floods due to monsoon precipitation (from July to September) and snow and glacier melt in summers (from April to September). With increasing temperature, snowmelt accelerates and precipitation patterns change. Resulting increases in runoff and discharge can cause floods in the Kabul River (Iqbal et al., 2018). Mean monthly river flows observed at the Attock rim station indicate that 4/5 of the annual flow occur during the April–September months with a peak in August (Iqbal et al., 2018). Flooding can transport large amounts of faecal waste (which often contains pathogenic organisms) from the land and contaminate the river. Most people in the river basin are connected to a sewer, but wastewater treatment has been dysfunctional ever since the waste water treatment plant in the basin was damaged by a large flood in 2010. Many livestock sheds are present in this area. Manure from these sheds is applied as fertilizer on agricultural fields, used for fuel or dumped directly into the river. Manure application on land is not regulated in the river basin. The Kabul River therefore carries untreated sewage effluents and manure from urban and rural settlements.

2.2. Water quantity and quality modelling

The SWAT hydrological model, together with its bacterial sub-model (Sadeghi and Arnold, 2002), was used to analyse the fate and transport

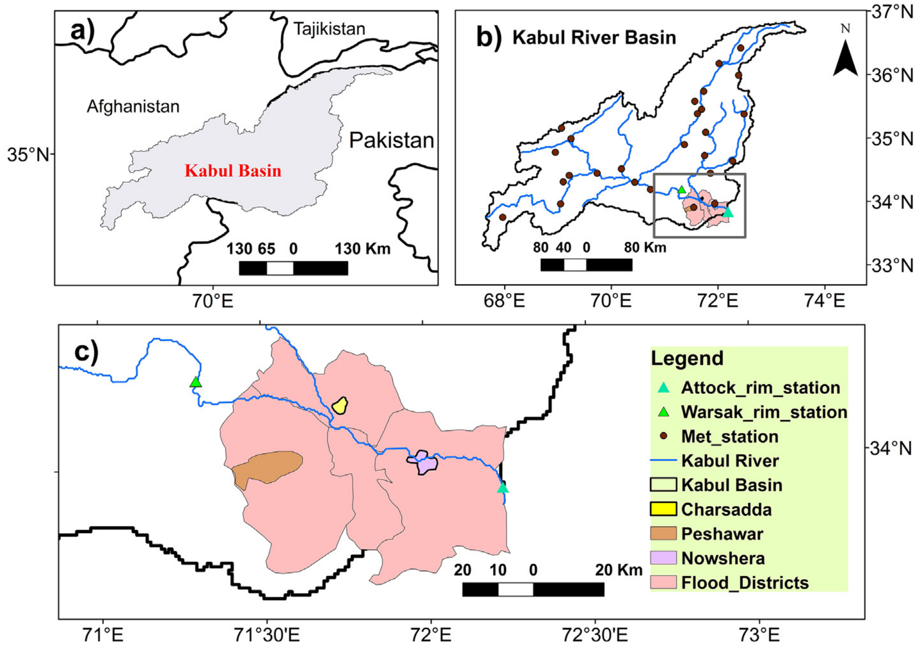

Fig. 1. Study map of the Kabul River Basin, the geography of the basin in Afghanistan and Pakistan, and the major tributaries of Kabul River. The triangles are the rim stations where discharge is measured. At the green point the Kabul River discharges into the Indus River. The cities Peshawar, Charsadda and Nowshera, which are main sources of faecal pollution, have been highlighted.

of *E. coli* in the lower Kabul River Basin. SWAT is a semi-distributed process based model that was developed to quantify the impact of management and climate on water resources, sediment and pollutant load in a catchment on a continuous time scale (Abbaspour et al., 2007). Its conceptual basis operates by distributing a watershed into sub-basins. Each sub-basin is linked via a stream network and further splits up into hydrological units. The model structure was built with the help of ArcGIS software, which provides geographical information of the watershed and allows for the definition of watershed hydrology. SWAT calculates potential evapotranspiration by applying the Penman-Monteith (Monteith, 1965) parameterization. The surface runoff from daily precipitation is computed with an altered curve-number method (Service, 1972), which calculates the quantity of runoff based on data for the local land use and soil types.

The SWAT bacterial model simulates the fate and transport of bacteria. To account for microbial loads in the catchment, point and non-point sources of bacterial pollution are included in the model. Runoff transports the non-point sources from the land to the river. The model calculates decay based on ambient temperature using first-order decay (Iqbal and Hofstra, 2018).

The SWAT model was previously calibrated and validated for hydrology (Iqbal et al., 2018) and *E. coli* concentrations (Iqbal and Hofstra, 2018) in Kabul River. The hydrology was modelled using upstream discharge data from the Warsak rim station (Fig. 1) that were acquired from the Water and Power Development Authority (WAPDA) of Pakistan as input and using a 90 m resolution Digital Elevation Model from the Shuttle Radar Topography Mission, European Space Agency's land cover data for 2009 and meteorological data acquired from the Pakistani Meteorological Department. A one-factor-at-a-time (Hogan et al., 2012) sensitivity analysis (Morris, 1991) was applied in the Sequential Uncertainty Fitting SUFI-2 algorithm SWAT-CUP automatic sensitivity analysis tool (Abbaspour, 2012). The most sensitive parameter was the curve number (CN) and a change in CN of 10% resulted in a discharge change of 20%. The SWAT model was calibrated for the 14 most sensitive parameters. The model was calibrated and validated using discharge data from the Attock rim station (Fig. 1) that were acquired from WAPDA. The model has been calibrated and validated for hydrology for 2007–2011 and 2012–2015 respectively. The model performance was good as measured and simulated flows correlated well, with an R^2 of 0.84 and 0.77 for calibration and validation respectively. The Nash-Sutcliffe Efficiency index (NSE) was 0.77 for calibration and 0.72 for validation. Percent bias (PBIAS) values were 22.2 and 17.7 for calibration and validation respectively. Peaks are slightly underestimated, particularly during the calibration period. Such underestimation is common in hydrological modelling (Iqbal et al., 2018).

The SWAT bacterial model was calibrated (April 2013 to June 2014) and validated (August 2014 to July 2015) on monthly time steps for monthly mean *E. coli* concentration. Unfortunately, the model could not be successfully calibrated and validated at a daily time step, despite the availability of high temporal resolution *E. coli* data (daily during peaks, biweekly throughout the year). Therefore we present the results for the monthly time step here. This has the disadvantage that peaks cannot be evaluated in detail. Long-term average trends are, though, the main focus of this first assessment. The observed *E. coli* concentrations used for the calibration and validation were collected on a bi-weekly time-step for the period April 2013–July 2015 (Iqbal et al., 2018) at nine locations along the river for the first year and five locations for the period thereafter. Standard most probable number (MPN) sampling (Iqbal et al., 2017) was used to detect *E. coli* concentrations. Details on the data can be found in Iqbal et al. (2017). The river is strongly contaminated with concentrations ranging from 820 to 160,000 cfu/100 ml.

The *E. coli* model for Kabul River included sewers and livestock sheds located along the river as point sources. Diffuse sources were agricultural lands that have been fertilized with manure. Upstream concentrations were observed concentrations near the Warsak rim station. The model was explained in detail in Iqbal and Hofstra (2018). Also for *E. coli* concentrations the most sensitive parameters (12 in total) were selected and the model was calibrated using SWAT-CUP. The modelling results corresponded well to measured concentrations in the Kabul River. The coefficients of determination (R^2) were 0.72 and 0.70, Nash-Sutcliffe efficiencies (NSE) were 0.69 and 0.66 and PBIAS values were 3.7 and 1.9 for *E. coli* concentration calibration and validation respectively.

2.3. Scenario analysis

To analyse the joint impacts of changes in socio-economic development and climate on *E. coli* concentrations, two scenarios have been developed. These scenarios are based on existing scenarios developed for the IPCC and include specific assumptions for the Kabul River Basin that are in line with the storylines. The scenarios were developed for the periods 2040–2060 (i.e. the 2050s) and 2080–2100 (i.e. the 2100s).

Since 2006, the climate change research community has established a new scenario framework (Ebi et al., 2014; Moss et al., 2010; O'Neill et al., 2014; Van Vuuren et al., 2014). The new scenarios comprise two basic elements: i) Shared Socio-economic Pathways (SSPs) and (ii) Representative Concentration Pathways (RCPs). The SSPs comprise narratives and quantifications of possible socio-economic developments. They have been structured around challenges to climate change mitigation and adaptation (O'Neill et al., 2014). The socio-economic variables that have been quantified include, for example, population, livestock production, urbanisation and GDP. The RCPs explore trajectories for the development of emissions and concentrations disturbing the radiative forcing of the climate system over time (Van Vuuren et al., 2011). Such disturbance in radiative forcing leads to changes in, among others, temperature and precipitation. In this paper we use combined SSP and RCP scenarios. Specific SSPs produce greenhouse gas emissions that can lead to one or more RCP. This results in a scenario matrix. Every cell in the scenario matrix portrays a reasonable course of emission and concentration and is compatible with socio-economic development pathways (Kok, 2016; Van Vuuren et al., 2014).

In this study, we only use two SSP-RCP combinations for the Kabul River Basin: SSP1 with RCP4.5 as the basis for Scenario_1 and SSP3 with RCP8.5 as the basis for Scenario_2. The SSP-RCP combinations chosen are plausible for this region. The combination SSP1 with RCP4.5 is often used. Scenario_1 is a scenario with a sustainability focus leading to limited climate change (i.e. adheres to the well-below 2 °C target). Strong socio-economic improvements are required for the Kabul River Basin and when the rest of the world also limits its greenhouse gas emissions, limited climate change is reasonable. Scenario_2 portrays large changes in climate by combining SSP3 with RCP8.5, which is globally not a common combination. In SSP3 society has such low economic growth and increases in energy access that greenhouse gas emissions are not high enough to reach the radiative forcing of 8.5 w/m^2 (Riahi et al., 2017). However, while the world overall could be on a socio-economic pathway that has very strong greenhouse gas emissions (e.g. SSP5), the Kabul River Basin could well be in a situation with war and poverty. So, combining SSP3 with RCP8.5 is a plausible combination for this region. While several SWAT model variables have been collated for the baseline, 2050s and 2100s from the SSP and RCP databases, also specific assumptions were made. These assumptions were made in line with the SSP narratives for Scenario_1 and Scenario_2. Table 1 summarises the data and the assumptions made for these scenarios that are detailed in Sections 2.3.1 and 2.3.2. The SWAT model was run for 20 year periods for the baseline (1990–2010) and for four climate model runs for Scenario_1 and 2 for the 2050s (2040–2060) and 2100s (2080–2100).

2.3.1. Socio-economic changes

E. coli concentrations are influenced by socio-economic changes. Scenario_1 is based on SSP1, which is called: "Sustainability – taking the green road" and emphasises human well-being, sanitation, education and improved water quality at the cost of long-term economic growth. In SSP1, population growth is moderate and urbanisation is well planned (Jiang and O'Neill, 2017).

Scenario_2 is based on SSP3. SSP3 is called: "Regional rivalry – a rocky road" and in the scenario the focus is on regional progress. Policy gradually shifts towards national security concerns, along with limited investment in education and other developments. This results in a slow economic growth, elevated poverty, and a decline in health care, safe water, improved sanitation and interest in environmental issues (O'Neill et al., 2015). Economic development is low and inequalities persist, especially in developing countries. The population growth is high in developing countries with unplanned urbanisation.

Table 1
Population growth, urbanisation, sanitation, wastewater treatment, land-use, livestock numbers and projected climate variables for Scenarios_1 and 2 for the 2050s and 2100s for the Kabul River Basin.

Scenario features	Base year	Scenario_1		Scenario_2	
	1990–2010	2050s	2100s	2050s	2100s
Population (million)	21.17	33.33	31.9	46.05	79.36
Urban population (%)	35.9	70.1	90.5	41.9	50.0
Connected to sewer (%)	90	99	99	99	99
Sewage treatment (%) based on connected to sewage system					
Primary (removal rate: 90%)	0	65	60	50	65
Secondary (removal rate: 99%)	0	20	20	0	0
Tertiary (removal rate: 99.9%)	0	0	10	0	0
No treatment (no removal)	100	15	10	50	35
Projected livestock number (million)					
Cattle (cow + buffalo)	0.89	1.17	1.06	1.46	1.88
Goats	1.15	2.91	2.54	3.01	4.41
Sheep	1.32	3.61	3.01	3.98	5.01
Manure treatment (%)					
Anaerobic digester (removal rate: 90%)	0	45	80	25	35
No treatment	100	55	20	75	65
Climate variables (ensemble mean)					
Total annual precipitation (mm)	285	328	370	341	356
Mean annual surface air temperature (°C)	22.9	24.8	26.0	25.9	28.1
Projected land use change (%)					
Agricultural land	33.1	29.8	25.8	36.4	37.6
Forest area	20.8	17.9	15.8	14.6	11.8
Urban/built-up area	21.3	29.4	36.4	27.9	30.2
Water/snow or ice	13.4	14.2	14.6	13.9	13.6
Barren/sparsely vegetation	11.4	8.7	7.4	7.2	6.8

The model input variables were adjusted for these two future narratives. The population numbers, urbanisation rate and change in livestock production have been taken from the SSP database (available at https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=welcome; accessed 23rd November 2016). These data are country data that we have downscaled. For population, the numbers for Pakistan and Afghanistan have been distributed over a 30 arc-second grid, using current and future country population, current and future urbanisation rates and the Land scan population database for 2010 (Bright et al., 2011). We assume that urban areas become more densely populated, but do not expand. Current livestock numbers in the study area obtained from the Bureau of Statists, Khyber Pukhtunkhwa (BSKP, 2016) have been adjusted with the percentage change in livestock production obtained from the SSP database. We assume that all livestock species increase by the same percentage, even though that is not necessarily realistic. At present there are no SSP data available for the different livestock species. We assume changes in population and livestock numbers, but we do not assume changes to the amount of *E. coli* they emit in their faeces.

Other input variables for the model have been quantified in line with the story lines for the SSPs. We make our own assumptions for sanitation, wastewater and manure treatment for our own scenarios. At present, most of the population living in urban and rural settlements in Kabul River Basin are connected to the sewage system (WATSAN, 2014). For both scenarios the assumption is that the percentages connected will increase. At present, there is no wastewater treatment, because the 2010 floods destroyed the systems (EPA-KP, 2014). Primary treatment systems are currently being developed. For Scenario_2 we therefore assume some degree of primary treatment. As Scenario_1 is much more focussed on sustainable development, we assume that

nearly all wastewater will be treated, with some degree of two level wastewater treatment (primary and secondary) by the 2050s and three level treatment (primary, secondary and tertiary) by the end of the century (see Table 1). Manure treatment will also reduce *E. coli* concentrations. We assume that in Scenario_1 most of the manure collected from livestock sheds is treated with an anaerobic digester prior to its use as fertilizer. In Scenario_2 the situation remains the same as today and no manure is treated. We use present removal rates in the treatment systems and do not account for possible technological advancements in *E. coli* removal in the treatment systems that could occur for Scenario_1.

Land-use change could also influence the *E. coli* concentrations in Kabul River. These should have been taken from the SSP database. Unfortunately, SSP land use change data were thus far unavailable. We therefore used RCP land use data, as explained below.

2.3.2. Climate change

E. coli concentrations will also be influenced by future climate change. Future climate projections for a given level of radiative forcing are uncertain due to numerous factors, such as climatic variations and regional climate-response patterns (Christensen et al., 2007; Meehl et al., 2007). We therefore use temperature and precipitation data from an ensemble of four different climate models. These climate models are INM-CM4, IPSL-CM5A, EC-EARTH, MIROC5 and they have been chosen for their earlier proven performance in the region as explained by Iqbal et al. (2018). The scenario data have been collected from the Earth System Grid Federation Portal (http://cmip-pcmdi.llnl.gov/cmip5/; https://esgf-data.dkrz.de/search/cmip5/ and have been downscaled using a delta change approach with quantile to quantile correction (Liu et al., 2015), as explained in more detail in Iqbal et al. (2018). Surface air temperature and precipitation are expected to increase in the basin for both scenarios according to Table 1. Precipitation events are expected to become more extreme.

RCP land use change data have been used, as these were, as far as the authors were aware, the only land use change data available at the time of the study. Land use data for scenario analysis were acquired from the RCP database (available on https://tntcat.iiasa.ac.at/RcpDb/dsd?Action=htmlpage&page=welcome#intro) for the 2050s and 2100s. For RCP4.5 the landuse data developed by the MiniCAM modelling team was selected. For RCP8.5 the landuse data developed by the MESSAGE modelling team was utilized to create the projected landuse data for the Kabul River Basin. In Scenario_1 agricultural areas (crop land and pasture), forest area and barren lands have been converted to urban settlements, while in Scenario_2 the agricultural land and urban settlement expand and forest area and barren land are reduced. Details are available in Table 1.

3. Results

Twenty year averaged SWAT model outputs are presented. Monthly mean *E. coli* loads and concentrations for the baseline period (1990–2010) have been compared with the near (2050s) and far (2100s) future for Scenario_1 and 2.

The 20 year average *E. coli* loads at Attock (near the inlet to the Indus River) range from 2.00×10^{12} (Scenario_1 for the 2100s) to 7.00×10^{12} cfu (Scenario_2 for the 2100s, see Fig. 2). For the baseline, human point sources account for 29%, livestock point sources for 15% and total non-point sources for 22% of the total load, and the remaining 34% of the loads are coming from upstream Warsak. Scenario_1 shows substantial reduction in *E. coli* loads by the 2050s and 2100s of −60% and −78%, respectively. Overall, the point sources account for 30% and 37.6%, while non-point sources account for 46% and 40.7% and loads from above Warsak for 24% and 21.7% by the 2050s and 2100s of the average loads respectively (Fig. 2).

With strong sanitation improvements in Scenario_1 loads of *E. coli* from point sources (human settlements and livestock sheds) are reduced, but non-point sources (livestock grazing and other agricultural activities) still strongly contribute to *E. coli* loads, despite some manure treatment in an anaerobic digester (Fig. 2). To control the *E. coli* loads from livestock sources, all the manure from livestock applied to the land should be treated (see Fig. 3, Scenario_1b). In that case, the Scenario_1 loads are reduced by 52% or the baseline loads are reduced by 90%. Also human and point livestock discharges could be reduced further when tertiary treatment is applied to human waste and all manure directly discharged is treated before discharge in the full basin. Then the total Scenario_1 loads are reduced by 94% of Scenario_1 (see Fig. 3, Scenario_1a). When both human and livestock discharges are reduced throughout the basin (see Fig. 3, Scenario_1c), *E. coli* loads are reduced by 96% compared to Scenario_1 and by 99.3% compared to the baseline loads.

The *E. coli* loads are expected to increase by 111% and 201% for Scenario_2 by the 2050s and 2100s compared to baseline *E. coli* loads respectively (Fig. 2). The contribution of the point, non-point and above Warsak loads are the same as for the baseline model. In the future, major contributors to *E. coli* loads are expected to be point sources due to increased population growth, unplanned urbanisation and limited wastewater treatment facilities, followed by expanded agricultural activities where untreated manure is used as organic fertilizer in the Kabul River Basin or dumped directly into the river.

Throughout the year, the loads vary between 12.0 and 12.9 log cfu for the baseline, 11.2 and 12.1 log cfu for Scenario_1 and 12.4 and 13.3 log cfu (colony forming unit) for Scenario_2 and peak in July and August (Fig. 4). The loads peak at the same time as the average discharge. This confirms that in this basin the increased runoff of manure into the river is the dominant response to increased precipitation.

For concentrations (Fig. 5), in particular in August, dilution also plays a role. Baseline monthly mean concentrations are high and vary between 4.8 and 5.1 log cfu/100 ml. Projections of surface air temperature, precipitation and river discharge were different for all General Circulation Models (GCMs) for the 2050s and 2100s. The GCMs were chosen for their characteristics and show a spread in climate responses. While the GCM INM-CM4 projects a relatively cold and dry future, IPSL-CM5A projects a cold and wet future. The GCMs EC-EARTH and MIROC5 project relatively warm futures. EC-EARTH projects a dryer future than MIROC5 (Iqbal et al., 2018)). Together these models provide a spread in future *E. coli* concentrations. Under colder conditions the concentrations are expected to be lower than under warmer conditions and under dryer conditions they are expected to be lower than under wetter conditions. While the spread over the four GCMs is in the order of 0.5–1 log-unit, the changes in *E. coli* concentrations all have the same sign, so we see decreases for Scenario_1 and increases for Scenario_2. Monthly and GCM mean *E. coli* concentrations for both scenarios are statistically significantly different from the baseline for the period 2100 (based on a Wilcoxon signed-rank test). For Scenario_1c the average concentration is 768 cfu/100 ml, which is still higher than the USEPA daily, single sample bathing water standards for *E. coli* in water samples (320 cfu/100 ml, USEPA, 2012).

4. Discussion

In this paper we used comprehensive socio-economic and climate change scenario analysis to assess future concentrations of *E. coli* in Kabul River. Currently, partly due to broken wastewater treatment systems, the *E. coli* concentrations are very high and strongly related to human inputs. We find that *E. coli* loads and concentrations are reduced in Scenario_1 and non-point livestock sources are relatively important for contamination of Kabul River, whereas in Scenario_2 *E. coli* loads and concentrations are higher than baseline concentrations, mostly due to an increased contribution of point sources. In the future we expect that if the sanitation situation is improved by installation of highly advanced wastewater and manure treatment plants the contamination to water sources would be reduced and the Kabul river water quality

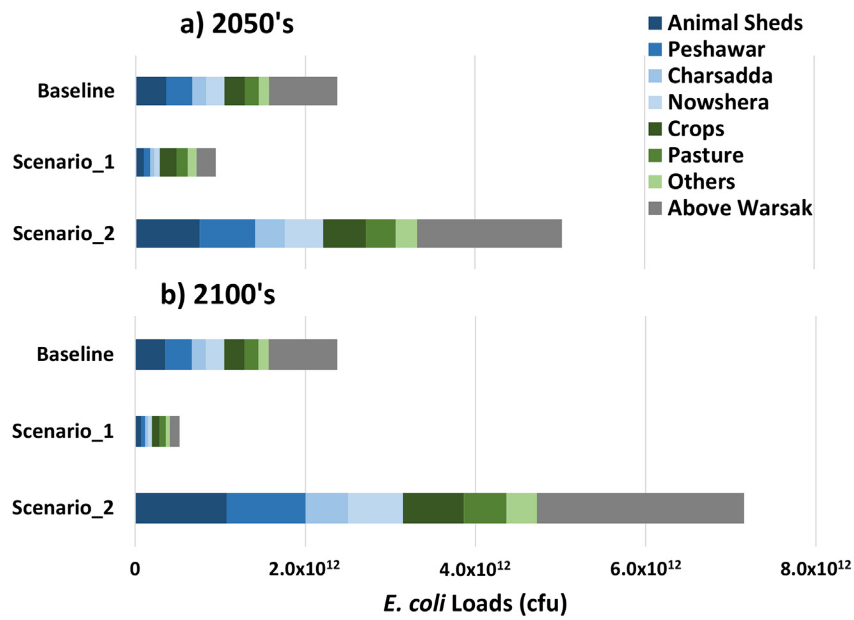

Fig. 2. *E. coli* loads in Kabul river at Nowshera for a) near future 2050s, b) far future 2100s. Loads are averaged over the four runs using the different GCM climate data and over the 20 years and 12 months. Point sources are depicted in blue, non-point sources in green and contribution of above Warsak concentrations in grey. The patterns indicate the contributions of various sub-sources of point and non-point contamination.

would be much improved. When wastewater and manure treatment are combined for the full basin (Scenario_1c), the total concentrations will strongly be reduced. These results are in line with our expectations.

Hydrological models coupled with bacterial modules are the best available tools to better understand the fate and transport of microbes from land to the river, as they take into account all the possible routes of contamination (Benham et al., 2006). The Soil and Water Assessment Tool (Moriasi et al., 2015) is a watershed-scale model. It has been widely used for modelling watershed hydrology at a continuous timescale. The SWAT bacterial model has also been used before for various watersheds worldwide to better understand the fate and transport of different pathogenic and non-pathogenic microorganisms (Coffey et al., 2010; Coffey et al., 2012; Sadeghi and Arnold, 2002; Tang et al., 2011). The model has been tested on a watershed in Missouri (USA) for *E. coli* and faecal coliforms (Baffaut and Benson, 2003). Likewise, Parajuli (2007) has tested the SWAT microbial model for a watershed in Kansas (USA). The model performed well in all of these studies (R^2 and NSE equal 0.5–0.74). In addition to the SWAT model several other bacterial models have been used to better understand the fate and transport of different bacterial species globally, such as the Watershed Assessment Model (WAM View) (Tian et al., 2002), Hydrologic Simulation Program in FORTRAN (HSPF) (Desai et al., 2011; Fonseca et al., 2014), WATFLOOD/SPL (Dorner et al., 2006), SENEQUE-EC model consists of the hydro-ecological SENEQUE/RIVERSTRAHLER model (Ouattara et al., 2013) and World Qual, Part of WaterGAP3 (Reder et al., 2015). Most of these models require many computing resources, which is an issue for modelling studies in data sparse developing countries like Pakistan. In such conditions the SWAT model is a good choice as it can be run with minimal input data for accurate modelling studies in those parts of the world and the results are comparable with other models (Devia et al., 2015).

Of course, like any other model, the SWAT model has uncertainties. One of the main uncertainties is the persistence in the model that currently only incorporates temperature-dependent decay. To better understand the uncertainties, a stochastic approach could be developed in which each input variable and parameter would get an uncertainty range and distribution, and the model is run multiple times with varying input variables and parameters in a Monte Carlo-like approach. This has been done before for SWAT hydrology, where they used multiple radar precipitation datasets (Sexton et al., 2010). This study did not aim to quantify uncertainties. Instead, we aimed to show a scenario analysis application using SWAT. The model calibration and validation results were classified as 'good' and we could therefore use the model in the scenario analysis.

Although SWAT is capable of simulating the influence of future socio-economic and climate change scenarios on *E. coli* concentrations,

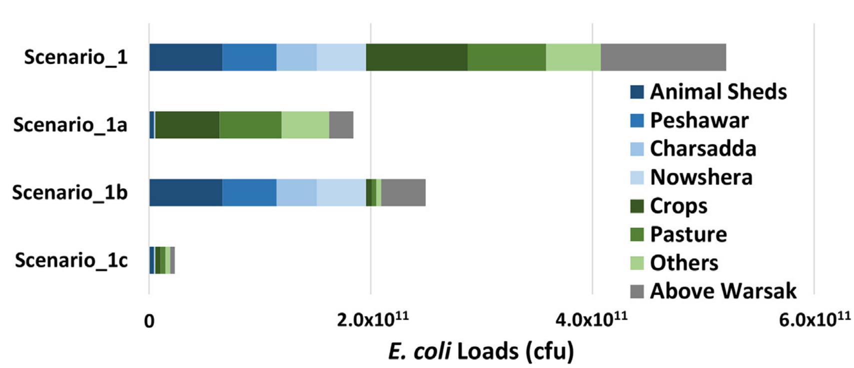

Fig. 3. Three variants of Scenario_1 compared with Scenario_1 *E. coli* loads for 2100. For further details, see Fig. 2.

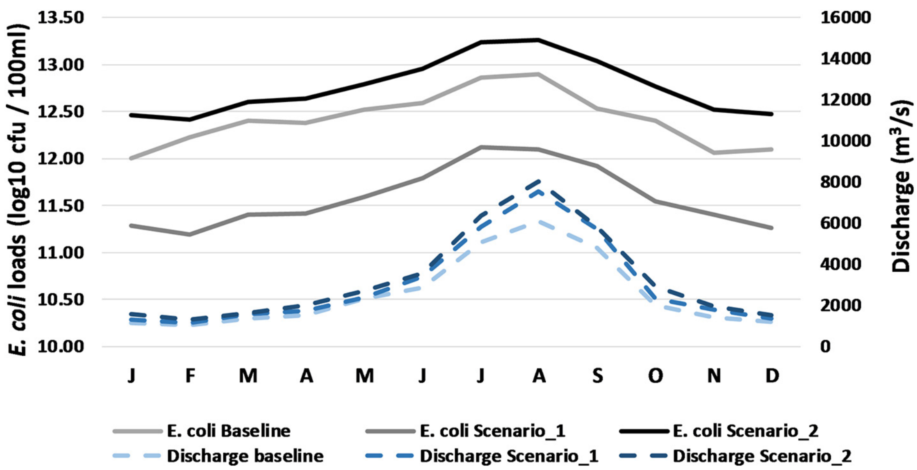

Fig. 4. Inter annual variability in *E. coli* loads for the baseline and 20 years averaged GCM means for Scenario_1 and 2 for 2100.

so far no studies have done that. Few studies have focused on scenario analysis. For instance Coffey et al. (2010) explored the influence of improvement of wastewater treatment reduction and found a 91% reduction of *E. coli* concentration to water sources from direct deposition and an 82% reduction from improved wastewater treatment system in the area. We found even slightly stronger reductions, with a 92% reduction in concentrations with increased manure treatment and a 96% reduction for concentrations with improved wastewater treatment and when both direct deposition and wastewater treatment were improved even a 99.3% reduction in *E. coli* concentration was observed in this study (see Fig. 3). The higher reduction in this study could be related to the greater pollution identified in the Kabul River compared to the Irish catchment modelled by Coffey et al. (2010). It should be noted that the stringent measures proposed in Scenario_1c are still insufficient to reduce the river water concentrations to below bathing water standards.

In the scenario development, Scenario_1 and 2 were developed using the most recent socio-economic and climate change scenarios that were developed for the IPCC. Other climate impact case studies used RCP4.5 and RCP8.5 as the two emission scenarios. RCP6.0 is barely used, as RCP4.5 and RCP8.5 overlap and cover the range of RCP6.0. The RCP selection is strongly limited by the availability of GCM runs. For instance, most of the GCMs have data for RCP4.5 and RCP8.5 (Kok, 2016). The GCMs selected by Iqbal et al. (2018) did not have data available for RCP2.6. This was one of reasons that RCP2.6 was not selected in the current study. Using the two reasonably extreme scenarios enables exploration of the spread of the *E. coli* concentrations in the future. However, the spread should not be seen as the full spread of plausible futures. To get a better understanding of the full spread, a full SSP-RCP matrix with the full GCM ensemble should be analysed. However, as the sign of the change in *E. coli* concentrations are the same for the different GCMs and as the two most extreme SSPs have been used, the added value of such an intensive model exercise is questionable.

We analysed changes in *E. coli* concentrations in the surface water of Kabul River using scenario data. For the Kabul River Basin population growth, urbanisation, livestock numbers and future land use data were acquired from SSP and RCP databases (explained in Section 2.3.2). The data were acquired for Pakistan and downscaled to

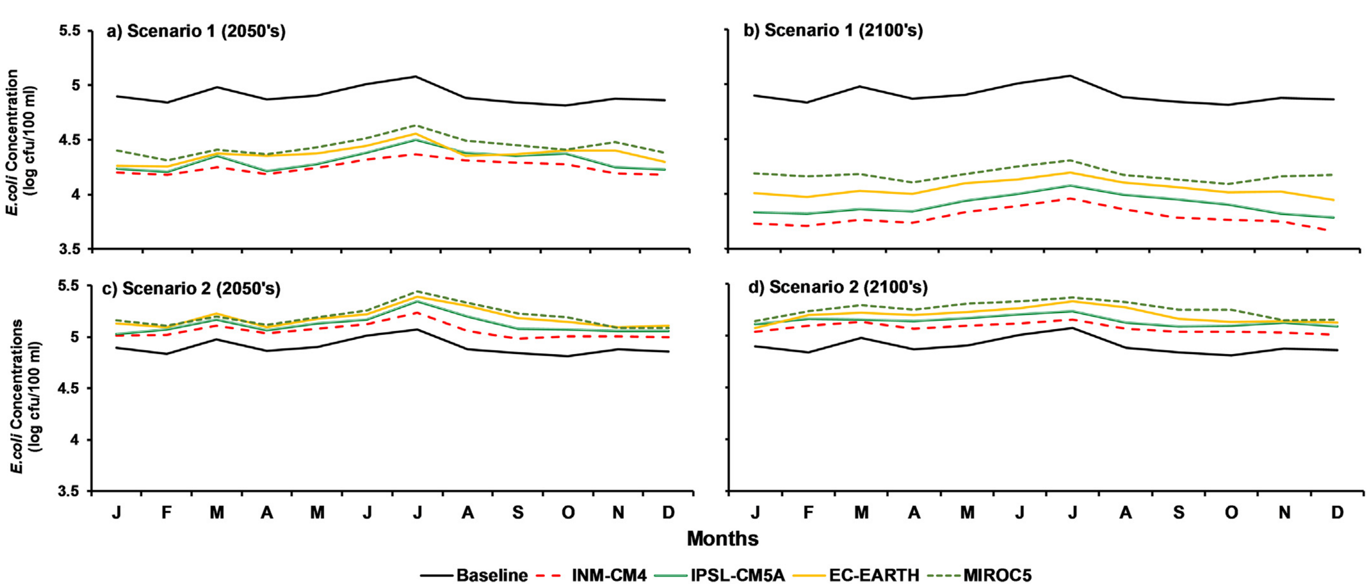

Fig. 5. Variability in monthly mean *E. coli* concentration in surface water of the Kabul River for four different GCM runs (INM-CM4, IPSL-CM5A, EC-EARTH, and MIROC5) for Scenario_1 and Scenario_2 averaged over the 20 years.

the Kabul River Basin. No data were available for sanitation, wastewater and manure treatment. Assumptions for these variables were made in line with the SSP storylines. In future studies, these variables could possibly be linked to other indicators, such as the GDP in the region that is also available through the SSP community. In addition, at present communities responsible for the SSP data using integrated assessment models are still finalising their model outputs. While we did use the most recently released data of October 2016, more and newer data may (Schets et al., 2011) become available in the near future.

Until now, a combined socio-economic and climate change scenario analysis was, as far as the authors are aware, only performed for *E. coli* concentrations in a small river in Bangladesh. Islam et al. (2018) conclude, like in this study, that *E. coli* concentrations increase in a future with strong population growth, limited environmental controls and large changes in the climate. In contrast, *E. coli* concentrations reduce when waste water treatment is improved. In the present study, manure management proved to be more important to reduce concentrations compared to the study in Bangladesh. The main reason for this, is that manure is a much more important source of contamination in the Kabul basin than in the small river in Bangladesh where human discharges are relatively much more important. Another difference is that the present study is done in a much larger river catchment and the river has much higher *E. coli* concentrations. This study provides an example in which socio-economic development and climate change scenario analysis are valuable for anticipating future changes and obtaining a better understanding of what is required to improve the current water quality. The study can be used as an example for others to apply similar tools to their own basin.

This paper focuses on *E. coli* rather than waterborne pathogens. This has the limitation that we cannot simply use the results to estimate health risk for the population and changes in this health risk due to socio-economic development and climate change. The method applied here, could, though, also be applied for pathogens. Using the modelling approach described here for pathogens, together with risk assessment in the future would improve our understanding of the future changes to human health risk. Such knowledge has already been requested for years (Campbell-Lendrum et al., 2009; Checkley et al., 2000; Hofstra, 2011; Semenza and Menne, 2009). Such papers would strongly contribute to the health risk chapter in IPCC's assessment report, which has thus far been very limited for waterborne disease. Overall, we could make the crude assumption that lower (higher) *E. coli* concentrations also means lower (higher) pathogen concentrations and thus lower (higher) health risk for the population. Scenario_1c should be the way forward to deal with the plausible changes and reduce the health risk for the population. Reaching concentrations as estimated by Scenario_1c is very important to achieve Sustainable Development Goal 3.2 that aims to improve the water quality.

5. Conclusions

In this paper, we assess future *E. coli* loads and concentrations in surface water using two scenarios based on the new IPCC scenario matrix approach with the SWAT model. Socio-economic variables together with climate change impacts will alter the *E. coli* loads and concentrations in the basin. We found changes in mean monthly *E. coli* loads and concentrations in surface water for the 2050s and 2100s for Scenario_1, its three variants Scenario_1a, 1b, 1c, and Scenario_2. In Scenario_2, with strong human and livestock population growth and limited wastewater and manure treatment improvements, *E. coli* concentrations are expected to increase by the 2050s and 2100s by 111% and 201% compared to baseline concentrations respectively. In Scenario_2 the source contributions are relatively the same as for the baseline. Point sources contribute 44%, nonpoint sources 22% and upstream loads contribute 34% to the loads. For Scenario_1, with moderate population growth, planned urbanisation and strong wastewater and manure treatment improvements, total *E. coli* loads by the 2050s and 2100s are expected to reduce by 60% and 78% compared to baseline loads. *E. coli* loads are further reduced in the three variants Scenario_1a (maximum point discharges reduction), Scenario_1b (maximum nonpoint discharges reduction) and Scenario_1c (both) by 92%, 90% and 99% compared the baseline loads. This shows that strong improvements in treatment will help to reduce the loads of *E. coli* in the Kabul River Basin. These reductions, though, do not reduce the concentrations to below bathing water standards and additional measures will remain essential.

Our scenario analysis demonstrates that in addition to anticipated climate change, socio-economic variables play a substantial role in microbiological contamination of water sources and they need to be considered in the future whenever water quality and related health risks are evaluated by water managers. This study is one of the first to combine socio-economic and climate scenarios to study the microbial water quality. The study provides an understanding of possible future changes and shows that stringent measures for human sewage and livestock manure are required to improve the water quality in the Kabul River Basin. The modelling and scenario approach described here can also be applied in other areas and for pathogens.

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References

Abbaspour, K., 2012. SWAT-CUP 2012: SWAT Calibration And Uncertainty Programs-A User Manual Eawag. Swiss Federal Institute Of Aquatic Science And Technology, Zurich, Switzerland.

Abbaspour, K.C., Yang, J., Maximov, I., Siber, R., Bogner, K., Mieleitner, J., et al., 2007. Modelling Hydrology and Water quality in the pre-alpine/alpine thur watershed using swat. J. Hydrol. 333, 413–430.

Baffaut, C., Benson, V.W., 2003. A bacteria tmdl for shoal creek using SWAT modeling and DNA source tracking. Total Maximum Daily Load TMDL Environmental Regulations II, pp. 35–40.

Benham, B.L., Baffaut, C., Zeckoski, R.W., Mankin, K.R., Pachepsky, Y.A., Sadeghi, A.M., et al., 2006. Modeling bacteria fate and transport in watersheds to support TMDLs. Trans. ASABE 49, 987–1002.

Boxall, A.B., Hardy, A., Beulke, S., Boucard, T., Burgin, L., Falloon, P.D., et al., 2009. Impacts of climate change on indirect human exposure to pathogens and chemicals from agriculture. Environ. Health Perspect. 117, 508.

Bright, E.A., Coleman, P.R., Rose, A.N., Urban, M.L., 2011. Landscan 2010. Digital Raster Data. Oak Ridge National Laboratory, Oak Ridge, TN.

BSKP, 2016. Bureau of Statistics, Khyber Pukhtunkhwa, Agricultural Report. Institute of Statistics.

Campbell-Lendrum, D., Bertollini, R., Neira, M., Ebi, K., McMichael, A., 2009. Health and climate change: a roadmap for applied research. Lancet 373, 1663–1665.

Checkley, W., Epstein, L.D., Gilman, R.H., Figueroa, D., Cama, R.I., Patz, J.A., et al., 2000. Effects of El Niño and ambient temperature on hospital admissions for diarrhoeal diseases in peruvian children. Lancet 355, 442–450.

Christensen, J.H., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, R., et al., 2007. Regional climate projections. Climate Change, 2007: The Physical Science Basis Contribution of Working group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. University Press, Cambridge, pp. 847–940 Chapter 11.

Coffey, R., Cummins, E., Cormican, M., Flaherty, V.O., Kelly, S., 2007. Microbial exposure assessment of waterborne pathogens. Hum. Ecol. Risk. Assess. 13, 1313–1351.

Coffey, Cummins E., Bhreathnach, N., Flaherty, V., Cormican, M., 2010. Development of a pathogen transport model for Irish catchments using SWAT. Agric. Water Manag. 97, 101–111.

Coffey, R., Dorai-Raj, S., O'Flaherty, V., Cormican, M., Cummins, E., 2012. Modeling of pathogen indicator organisms in a small-scale agricultural catchment using SWAT. Hum. Ecol. Risk Assess. Int. J. 19, 232–253.

Desai, A., Rifai, H.S., Petersen, T.M., Stein, R., 2011. Mass balance and water quality modeling for load allocation of *Escherichia coli* in an urban watershed. J. Water Resour. Plan. Manag. 137, 412–427.

Devia, G.K., Ganasri, B.P., Dwarakish, G.S., 2015. A review on hydrological models. Aquat. Procedia 4, 1001–1007.

Dorner, S.M., Anderson, W.B., Slawson, R.M., Kouwen, N., Huck, P.M., 2006. Hydrologic modeling of pathogen fate and transport. Environ. Sci. Technol. 40, 4746–4753.

Ebi, K.L., Hallegatte, S., Kram, T., Arnell, N.W., Carter, T.R., Edmonds, J., et al., 2014. A new scenario framework for climate change research: background, process, and future directions. Clim. Chang. 122, 363–372.

EPA-KP, 2014. An Act to Provide for the Protection, Conservation, Rehabilitation and Improvement of the Environment, for the Prevention and Control of Pollution, and Promotion of Sustainable Development in the Province of the Khyber Pakhtunkhwa. Govenment Press, Khyber Pukhtunkhwa:Provincial Assembly KP.
Fonseca, A., Botelho, C., Boaventura, R.A., Vilar, V.J., 2014. Integrated hydrological and water quality model for river management: a case study on Lena River. Sci. Total Environ. 485, 474–489.
Graham, J.P., Polizzotto, M.L., 2013. Pit latrines and their impacts on groundwater quality: a systematic review. Environ. Health Perspect. 121, 521–530.
Hofstra, N., 2011. Quantifying the impact of climate change on enteric waterborne pathogen concentrations in surface water. Curr. Opin. Environ. Sustain. 3, 471–479.
Hofstra, N., Vermeulen, L.C., 2016. Impacts of population growth, urbanisation and sanitation changes on global human Cryptosporidium emissions to surface water. Int. J. Hyg. Environ. Health 219, 599–605.
Hogan, J.N., Daniels, M.E., Watson, F.G., Conrad, P.A., Oates, S.C., Miller, M.A., et al., 2012. Longitudinal poisson regression to evaluate the epidemiology of Cryptosporidium, Giardia, and fecal indicator bacteria in coastal California wetlands. Appl. Environ. Microbiol. 78, 3606–3613.
Iqbal, M., Hofstra, N., 2018. Modelling *Escherichia coli* fate and transport in the Kabul River Basin using SWAT. Hum. Ecol. Risk. Assess https://doi.org/10.1080/10807039.2018.1487276 (In Press).
Iqbal, M.S., Ahmad, M.N., Hofstra, N., 2017. The relationship between hydro-climatic variables and *E. coli* concentrations in surface and drinking water resources in the Kabul River Basin Pakistan. AIMS Environ. Sci. 4, 690–708.
Iqbal, M., Dahri, Z., Querner, E., Khan, A., Hofstra, N., 2018. The impact of climate change on flood frequency and intensity in the Kabul River Basin. Hydrology in River Basins: developments in Science and Application (HRBDSA). Geosciences 8, 114–122.
Islam, M.M., Iqbal, M.S., Leemans, R., Hofstra, N., 2018. Modelling the impact of future socio-economic and climate change scenarios on river microbial water quality. Int. J. Hyg. Environ. Health 221, 283–292.
Jalliffier-Verne, I., Leconte, R., Huaringa-Alvarez, U., Heniche, M., Madoux-Humery, A.-S., Autixier, L., et al., 2017. Modelling the impacts of global change on concentrations of *Escherichia coli* in an urban river. Adv. Water Resour. 108, 450–460.
Jiang, L., O'Neill, B.C., 2017. Global urbanisation projections for the shared socioeconomic pathways. Glob. Environ. Chang. 42, 193–199.
Kok, K., 2016. Multi-scale integration and synthesis of scenarios and adaptation narratives. Econadapt deliverable 1.5. Wageningen University, Wageningen.
Liu, C., Hofstra, N., Leemans, R., 2015. Preparing suitable climate scenario data to assess impacts on local food safety. Food Res. Int. 68, 31–40.
Meehl, G.A., Stocker, T.F., Collins, W.D., Friedlingstein, P., Gaye, A.T., Gregory, J.M., et al., 2007. Global climate projections. Climate Change 3495, 747–845.
Monteith, J., 1965. Evaporation and environment. Proceedings of the Symp Soc Exp Biol. 19.
Moriasi, D.N., Gitau, M.W., Pai, N., Daggupati, P., 2015. Hydrologic and water quality models: performance measures and evaluation criteria. Trans. ASABE 58, 1763–1785.
Morris, M.D., 1991. Factorial sampling plans for preliminary computational experiments. Technometrics 33, 161–174.
Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., van Vuuren, D.P., et al., 2010. The next generation of scenarios for climate change research and assessment. Nature 463, 747–756.
Odonkor, S.T., Ampofo, J.K., 2013. *Escherichia coli* as an indicator of bacteriological quality of water: an overview. Microbiol. Res. 4, 2.
O'Neill, B.C., Kriegler, E., Riahi, K., Ebi, K.L., Hallegatte, S., Carter, T.R., et al., 2014. A new scenario framework for climate change research: the concept of shared socioeconomic pathways. Clim. Chang. 122, 387–400.
O'Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., et al., 2015. The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century. Glob. Environ. Chang. 42, 169–180.
Ouattara, N.K., de Brauwere, A., Billen, G., Servais, P., 2013. Modelling faecal contamination in the Scheldt Drainage Network. J. Mar. Syst. 128, 77–88.
Parajuli, P.B., 2007. SWAT Bacteria Sub-model Evaluation and Application. ProQuest Information and Learning Company, United States.
Rankinen, K., Butterfield, D., Sànchez, M.F., Grizzetti, B., Whitehead, P., Pitkänen, T., et al., 2016. The INCA-pathogens model: an application to the Loimijoki River Basin in Finland. Sci. Total Environ. 572, 1611–1621.
Reder, K., Flörke, M., Alcamo, J., 2015. Modeling historical fecal coliform loadings to large European rivers and resulting in-stream concentrations. Environ. Model. Softw. 63, 251–263.
Riahi, K., Van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B.C., Fujimori, S., et al., 2017. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: an overview. Glob. Environ. Chang. 42, 153–168.
Ridley, J., Wiltshire, A., Mathison, C., 2013. More frequent occurrence of westerly disturbances in Karakoram up to 2100. Sci. Total Environ. 468, S31–S35.
Rose, J.B., Epstein, P.R., Lipp, E.K., Sherman, B.H., Bernard, S.M., Patz, J.A., 2001. Climate variability and change in the United States: potential impacts on water-and foodborne diseases caused by microbiologic agents. Environ. Health Perspect. 109, 211.
Sadeghi, A.M., Arnold, J.G., 2002. A SWAT microbial sub-model for predicting pathogen loadings in surface and groundwater at watershed and basin scales. Proceedings of the Total Maximum Daily Load (TMDL): Environmental Regulations, Proceedings of 2002 Conference, 2002. American Society of Agricultural and Biological Engineers, pp. 56–63.
Schets, F., de Roda Husman, A., Havelaar, A., 2011. Disease outbreaks associated with untreated recreational water use. Epidemiol. Infect. 139, 1114.
Semenza, J.C., Menne, B., 2009. Climate change and infectious diseases in Europe. Lancet Infect. Dis. 9, 365–375.
Service USSC, 1972. SSC National Engineering Handbook, Section 4: Hydrology. University of Minnesota, USA: The Service.
Sexton, A., Sadeghi, A., Zhang, X., Sirnivasan, R., Shirmohammadi, A., 2010. Using NEXRAD and Rain Guage Precipitation Data for Hydrological Calibration of SWAT in a Northeastern Watershed. 53. American Society of Agricultural and Biological Engineers (ASABE), pp. 1501–1510.
Sterk, A., Schijven, J., de Roda Husman, A.M., de Nijs, T., 2016. Effect of climate change on runoff of Campylobacter and Cryptosporidium from land to surface water. Water Res. 95, 90–102.
Tang, J., McDonald, S., Peng, X., Samadder, S.R., Murphy, T.M., Holden, N.M., 2011. Modelling Cryptosporidium oocysts transport in small ungauged agricultural catchments. Water Res. 45, 3665–3680.
Tian, Y.Q., Gong, P., Radke, J.D., Scarborough, J., 2002. Spatial and temporal modeling of microbial contaminants on grazing farmlands. J. Environ. Qual. 31, 860–869.
UN, 2015. Levels and trends in child mortality - child mortality estimates. http://www.Childmortality.Org/files_v20/download/igme%20report%202015%20child%20mortality%20final.Pdf, Accessed date: 7 May 2017.
USEPA, 2012. Recreational water quality criteria. EPA-820-F-12-061. Office of Water. United States Environmental Protection Agency, Washington, Washington, DC.
Van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., et al., 2011. The representative concentration pathways: an overview. Clim. Chang. 109, 5–31.
Van Vuuren, D.P., Kriegler, E., O'Neill, B.C., Ebi, K.L., Riahi, K., Carter, T.R., et al., 2014. A new scenario framework for climate change research: scenario matrix architecture. Clim. Chang. 122, 373–386.
Vörösmarty, C.J., McIntyre, P.B., Gessner, M.O., Dudgeon, D., Prusevich, A., Green, P., et al., 2010. Global threats to human water security and river biodiversity. Nature 467, 555–561.
WATSAN, 2014. Water and sanitation at Khyber Pukhtunkhwa. http://www.Urbanpolicyunit.Gkp.Pk/water-and-sanitation/, Accessed date: 24 March 2017.
Whitehead, P., Wilby, R., Battarbee, R., Kernan, M., Wade, A.J., 2009. A review of the potential impacts of climate change on surface water quality. Hydrol. Sci. J. 54, 101–123.
Wiltshire, A., 2014. Climate change implications for the glaciers of the Hindu Kush, Karakoram and Himalayan region. Cryosphere 8, 941–958.
Wu, J., Long, S., Das, D., Dorner, S., 2011. Are microbial indicators and pathogens correlated? A statistical analysis of 40 years of research. J. Water Health 9, 265–278.